Preliminary Bounding Experiments in a Dynamic Hexapod

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Abstract. This paper describes the implementation of a preliminary bounding gait in a small hexapod, RHex [1], with compliant legs. A four-legged bounding gait, which uses only the front and back leg pairs, achieves an average speed of 1.5 m/s and a low specific resistance. Leg touchdown angles and desired stance trajectories are fixed a priori. The only feedback employed is leg angle sensing and touchdown detection. With no explicit controller-level synchronization between the front and back leg pairs, stable pitch oscillations are obtained from the excited natural dynamics of the system.

1 Introduction

The RHex design and control were inspired by the study of cockroach locomotion [2][3] and the minimal design complexity ideas for legged robots (single actuator compliant legs) developed at the Ambulatory Robotics Lab [4,5]. Some of the key biologically inspired functions [6] have been applied through the mechanical simplicity of a single actuator per leg and the use of largely open-loop, clock-driven gaits [1]. This simplicity has resulted in a reliable system that can be used in real-world situations – outside of the controlled lab environment.

A bounding gait is characterized by a pairing of the fore and hind leg pairs such that the two act simultaneously, as a single leg. Few groups have produced bounding gaits in robots – Raibert's [7] quadruped used the concept of virtual legs, symmetry and partitioned controllers to achieve a bounding gait. Scout II [5,8] at McGill made advances in power and computation autonomy, and control, with a mechanically simple machine. Also, Scout II was to our knowledge the first, and is to date still the only existent power autonomous quadruped robot capable of bounding. Kimura [9] built a small quadruped, Patrush, whose bounding dynamics were excited by neural oscillator signals. Recently, researchers at Sony and Boston Dynamics Inc. implemented a bounding gait on a modified AIBO entertainment quadruped [10].

RHex, our six-legged robot, joins these few bounding robots by adding a quadrupedal bounding gait, utilizing the front and rear leg pairs of legs, to its already large repertoire of gaits. These currently include walking on even and highly irregular terrain [1], stair-climbing [11,12], swimming, flipping [13] and pronking [14]. Dynamic running gaits, such as bounding and pronking, make

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explicit use of our robot's compliant legs, and have the potential for increased speed and energy efficiency, when compared to static walking tripod gaits.

2 RHex Platform Description

RHex is a power and computation autonomous hexapod with a single actuator per compliant leg. Figure 1 shows the basic configuration of RHex and table 1 summarizes most of the important dimensions. The half-circle legs that RHex currently uses are the result of numerous design iterations searching for a robust, compliant leg design whose form (shape) supports the wide variety of functions the legs provide over the range of robot behaviours [12]. Compliance is important for dynamic legged gaits because it allows the energy that would otherwise be lost in impacts with the ground to be stored for release in a later phase of the motion.

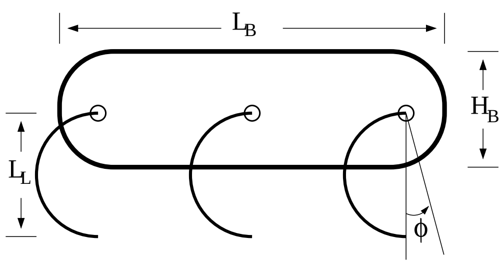

Fig. 1. Key dimensions of RHex

Table 1. Basic RHex Characteristics

Parameter	Notation	Value
Body Mass	M_B	7.5 kg
Body Length	L_B	0.51 m
Body Height	H_B	0.13 m
Leg Mass	M_L	0.08 kg
Leg Length (unloaded)	L_L	0.16 m
Leg Spring Constant (Linear Approximation)	K_L	1900 N/m
Maximum Hip Torque	τ_{max}	7 Nm
Maximum Hip Speed	ω_{max}	5 rev/s

3 Basic Controller

Inspired by successes of the controllers in the Scout II quadruped that excite the robot's passive dynamics [5], the controller used for bounding has two different states for each of the front and back pairs of legs – the middle legs are kept out of the way for the duration of the bounding gait – without the notion of an overall body state for control.

Gait Parameters

Both front and rear pairs of legs are assumed to be in flight initially. During this state, the legs are servoed via a set point PD loop to a touchdown angle, ϕ_{td}, relative to the body perpendicular. In order for the touchdown event to take place, both legs in a pair are required to have made contact with the ground. This is done so as to reduce the roll moment that would be created if the left or right leg made contact with the ground – initiating the next phase – before the other is near enough to the ground to exert force. It may, however, cause the same roll moment due to uneven compression of the legs at touchdown if the roll angle of the robot is too large. When the touchdown requirements are met, the leg pair sweeps at a fixed desired rate, $\dot{\phi}$, until the sweep limit, ϕ_{lim}, is reached. Since no lift-off sensing is implemented, the sweep limit is set to occur after the legs lift off. After the leg pair leaves the ground, it returns during flight to the touchdown angle as from the initial condition.

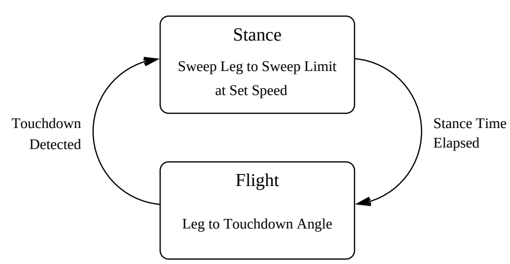

Fig. 2. A graphical representation of the state machine controlling the bounding behaviour

Through experimentation coupled with high-speed video analysis, the parameters in Table 2 were found that result in a stable bounding gait. The main bounding gait control parameters are the leg pairs touchdown angles and sweep speeds. Generally, the larger the touchdown angle, the larger the amount of the forward kinetic energy (forward speed) that is transferred to vertical energy (hopping height) for that particular hip. The tuning procedure aims at adjusting the four main parameters (two touchdown angles and

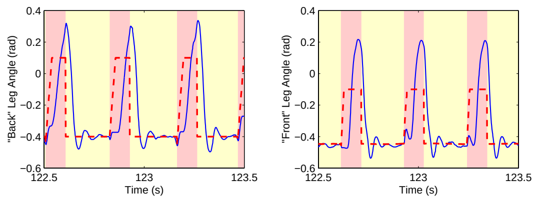

Fig. 3. Commanded leg trajectories (dashed line) and actual leg angles (solid line) from a bounding experiment. Shaded background indicates the stance phase for that leg

two sweep speeds) such that the front and back hip vertical hopping height is sufficient to achieve leg ground clearance, but low enough to maintain stability. In addition, the parameters need to be adjusted that both front and back hips achieve the same vertical oscillation amplitudes. Once this was accomplished, the robot's bounding motion was achieved (albeit still with low repeatability), where the pitching oscillation was stabilized via the robot's passive dynamics. Since the current controller is tuned for only one particular speed, and its domain of attraction is limited, the success of the algorithm depends in no small manner on the skill of the experimenter in launching the robot to initialize its motion close enough to the desired one. Naturally, developing bounding controllers for a continuum of forward speeds will solve this problem, and is of paramount importance for our near-term research.

Table 2. Bounding Gait Parameters

Parameter	Notation	Value	
		Front	Rear
Touchdown Angle	ϕ_{td}	-0.45 rad	-0.4 rad
Sweep Speed	$\dot{\phi}$	22 rad/s	17 rad/s
Proportional Gain	K_p	35 Nm/rad	35 Nm/rad
Derivative Gain	K_d	0.35 Nm/(rad/s)	0.35 Nm/(rad/s)

Touchdown Detection

The morphology of the leg used on the robot and the fully-recirculating nature of some of the gaits used on RHex make simple switch- or strain-based touchdown detection difficult. Instead, a virtual sensor based on an estimate of the motor current is used, which was developed for the pronking gait on RHex [14]. By thresholding this current, the joint error that arises when the toe makes contact with the ground can be detected.

The current in the motor is given by

$$i_{motor} = \frac{V_{motor} - Emf}{R_a + R_{drive}}, \tag{1}$$

where V_{motor} is the terminal voltage applied to the motor, Emf is the electromotive force created by the spinning rotor and given by $K_s \cdot \omega$. R_a and R_{drive} are the resistances of the armature and the drive electronics, respectively. While V_{motor} is not measured directly, it can be written as $V_{motor} = D \cdot V_{batt}$ where D is the duty cycle of the drive and is commanded explicitly by the control software. V_{batt} is the battery voltage, approximated as a constant to avoid sensor reliability problems. The remainder of the terms are measured, or, in the case of ω, taken as the derivative of angular position.

With the current estimated, a state machine is built around each leg to keep track of the leg status. If the current corresponding to a leg awaiting touchdown exceeds a threshold value, it is determined to have made contact with the ground, and entered the stance phase. When it is determined that the stance phase for a leg has finished, the state is set to a 'retraction' phase, where it remains until the current estimate drops below a determined value, for a set period of time. This decreases the likelyhood of self-triggering when the leg is commanded to the touchdown angle at the end of the flight phase. When the current makes this drop, the touchdown detection is 're-armed,' ready for the next event. The parameters used for the touchdown detection are summarized in table 3 and some resulting trigger events can be seen in the estimated current plot of fig. 4.

Table 3. Touchdown Detection Thresholds

Parameter	Notation	Value
Trip Current	i_t	2.5 A
Release Current	i_r	0.8 A
Settling Time	t_s	0.01 s

The transition event from stance to flight cannot be based on whether the toes are in contact with the ground using the virtual sensor based on motor current. The estimation method and the large current that is commanded during this phase make robust 'lack-of-ground' detection difficult. Instead, a time-driven event is used. A specified amount of time after the touchdown event has occurred, it is assumed that the pair of legs is no longer in stance. The state-machine returns to the first phase, where a touchdown angle is tracked.

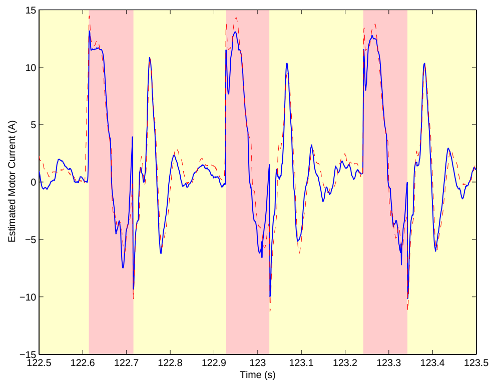

Fig. 4. Estimated motor current for the two front legs and the state of the pair as determined by the virtual sensor, where the shading indicates the stance phase

Resultant Gait

With the controller tuned, trials reveal the form that a bounding gait takes on RHex. Driven by a simple controller, the robot exhibits a periodic oscillation in the pitch axis. Occasional failures (missteps) are recoverable without operator intervention. The contact pattern of the legs is illustrated in fig. 5. The

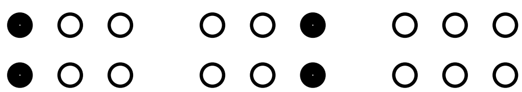

Fig. 5. Foot-contact pattern for the Bounding Gait. A solid circle indicates ground contact. Robot traveling from left to right

best view of what the robot does is obtained from the following key frames captured with a high speed camera (fig. 6). Note that the robot traverses the frame from right to left while the frame sequence is presented from left to right, top to bottom.

4 Energetics and Reliability

To quantify the efficiency of locomotion of various gaits in various organisms and machines, the specific resistance is useful [15]. This unitless measure of the energetic cost of locomotion can be expressed as

$$\varepsilon = \frac{P}{mgv}, \tag{2}$$

where P is the average total electrical power drawn from the batteries, m is the mass of the robot, g is the gravitational acceleration and v is the forward speed.

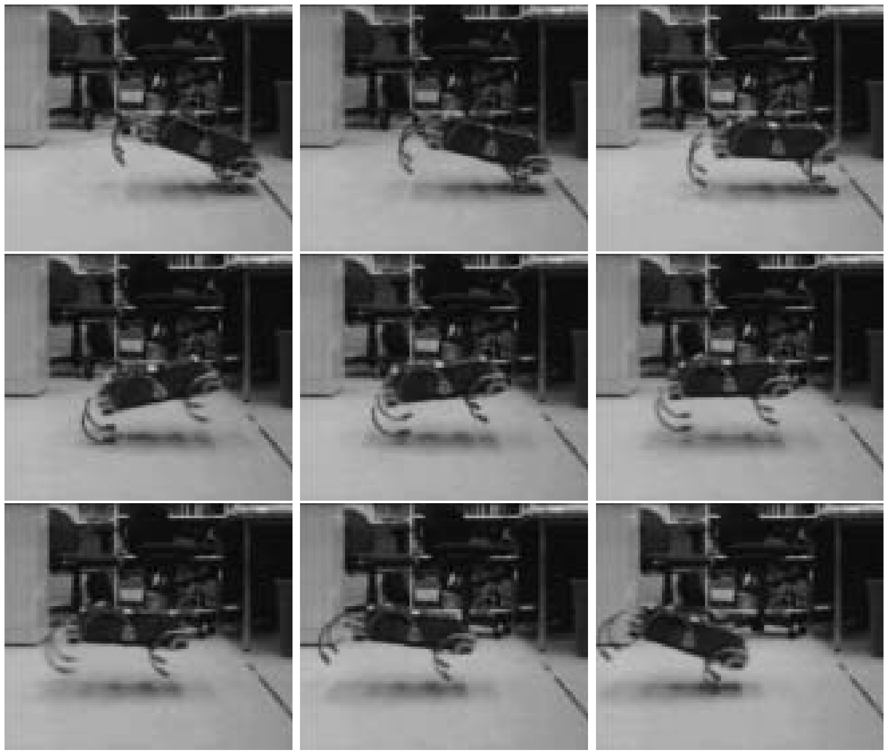

Fig. 6. Bounding motion in RHex at approximately 1.4 m/s. Robot moves from right of frame to left while the sequence is presented in reading order. Frames 0.024 s apart on average

Testing was performed to measure average power consumption and speed of the behaviour over a 2 m stretch of linoleum flooring. Thirty-seven trials were classified into four categories based on video review and average speed. Of the experiments, 24% were discarded due to failure to cross the second timing mark or suspicion of interference from initial conditions. 35% had poor speed – less than 1 m/s – due to stumbling or excessive deviation from a straight-line path. 19% performed with a speed in the range 1.0–1.4 m/s, though not necessarily with a stable bounding gait. The remaining runs exhibited a speed between 1.4 and 1.6 m/s and had a stable bounding cycle. The strongest factor in the success of the run is believed to be the initial launch provided by the operator. Table 4 summarizes the results, while fig. 7 compares the energetics to other gaits on RHex.

Figure 8 shows that the power use occurs in very large spikes when the legs interact with the ground. During flight, little power is used. This suggests that by decreasing the duty cycle of the bound, that is, spending a smaller fraction of the cycle on the ground, power consumption could be improved.

Table 4. Bounding Energetics

Frequency	Mean Speed	Mean Specific Resistance
9	Failed Trials (N/A)	
13	0.67 m/s	4.35
7	1.21 m/s	2.37
8	1.50 m/s	2.08

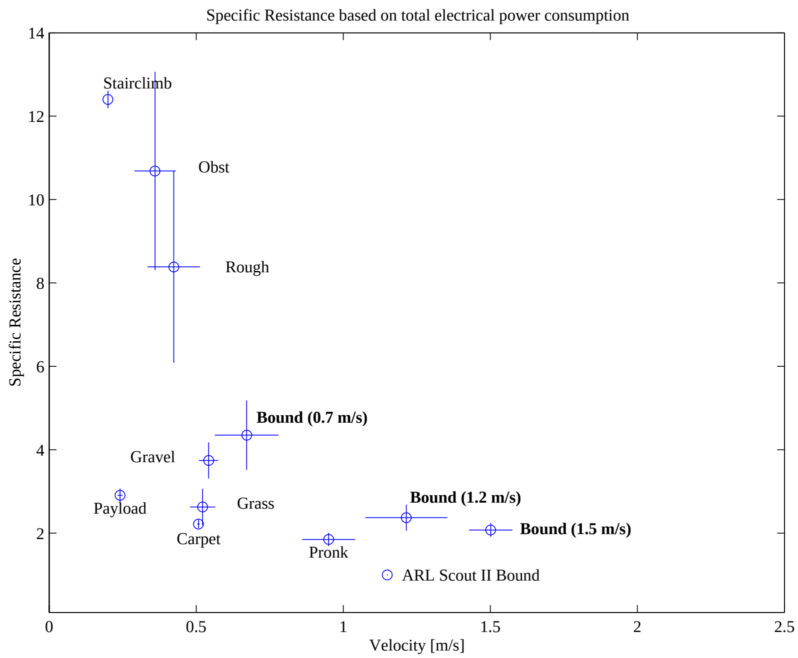

Fig. 7. Specific resistance values for different gaits on different surfaces for RHex and Scout II [1][5][12][14]. Error bars indicate standard deviation

A better estimate or measurement of stance time would also help by allowing better matching between the robot's actions and the controller's. Rather than using a set point control for the touchdown angle, a trajectory could be generated, bringing the leg from the sweep angle to touchdown in a smooth motion, also decreasing power consumption.

5 Conclusions and Future Work

A simple quadruped bound gait has been implemented on the hexapod RHex. While reliability is not yet high, 40% of the 37 formal tests performed show an average speed in excess of 1 m/s or 2 body lengths/s and roughly half

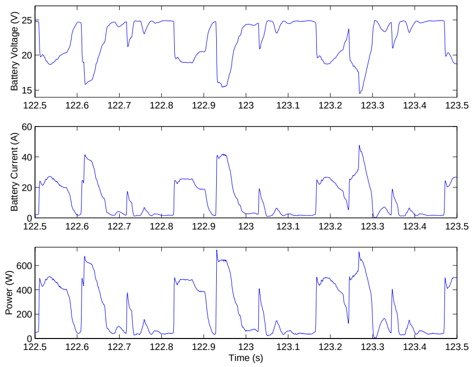

Fig. 8. Closeup view of power data from one portion of a successful run at 1.5 m/s

of these performed with a very fluid, natural-looking motion. The gait is efficient compared to other gaits on RHex in terms of specific resistance, with a minimum value of 2.08 averaged over the trials that reached the 1.4–1.6 m/s speed range.

Future enhancements of interest are controllers for wider ranges of speed, and/or a startup algorithm to improve the consistency of the initial conditions seen by the bounding controller, with the expectation that this will improve the overall reliability and performance. Further investigation of the stance phase may yield a better estimate of the stance time, and the opportunity to use the contact events more efficiently. A better understanding of the lift-off conditions will allow an estimate of flight time, and from this a trajectory could be commanded for the touchdown angle control, with the aim to reduce power consumption. Use of a pitch sensor will allow more sophisticated control algorithms to be attempted, such as controlling the leg angle with respect to the ground, rather than the body-perpendicular. Testing on varied terrain will also be performed.

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